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A swine model of pulmonary embolism with human-derived thrombi

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ABSTRACT

Objectives: The development and evaluation of percutaneous thrombectomy devices for pulmonary embolism (PE) pose a need for standardized large *in vivo* models with representative anatomical and physiological conditions and clots analogs. In this study, we present a swine model of PE model employing human-derived clot analogs.

Material and Methods: Baseline angiographic and physiological pressure measurements were obtained in six adult Yorkshire pigs (45–65 kg) and results were benchmarked for interspecies comparison with published human data using fluoroscopic examinations, intra-arterial pressure measurements, and histologic studies. Then, clot analogs were created *ex vivo* employing banked human blood and a subset incubated in iodinated contrast for fluoroscopic visualization. Clot analogs were then embolized via a femoral venous access and angiographic/physiological consequences were evaluated.

Results: The main, right, and left pulmonary artery diameters were 24 ± 1.1 mm, 16.5 ± 0.8 mm, and 12.6 ± 1.2 mm, respectively. The angle between the main pulmonary artery at the bifurcation point was approximately 90–95°. The clot analogs were heterogeneous and had increased fibrin content along the clot length. The overall composition was 96.63% red blood cell (RBC)/3.37% fibrin in the initial section, 48.85% RBC/51.15% fibrin in the intermediate section, and 3.44% RBC/96.56% fibrin in the final section. Embolization of the clot analogs resulted in distal occlusion of the right and left pulmonary arteries.

Conclusions: This swine model coupled with clot analog is able to accurately mimic human anatomical and physiological conditions in PE making it feasible for the evaluation of pulmonary thrombectomy devices.

Keywords: Pulmonary embolism, Animal model, Endovascular treatment, Thrombi

INTRODUCTION

Pulmonary embolism (PE) and deep vein thrombosis continue to be a major cause of morbidity and mortality in the United States, with more than 300,000 cases/year.[1,2] In the setting of high-risk submassive and massive PE, the use of systemic thrombolytic agents has been on of the mainstream strategies but is associated with an increased risk of hemorrhagic complications.[3] Open surgical pulmonary embolectomy is another option but usually only available at tertiary care facilities; it requires cardiopulmonary bypass and has inherent surgical

risks such as infection, hemorrhage, and/or long in-hospital recovery times.[4,5]

Recently, catheter-based thrombectomy devices have been introduced to treat PE percutaneously. Compared to thrombolytic therapies, endovascular thrombectomy is associated with a reduced risk of hemorrhage and a reduced need for thrombolytic agents.[6] As in any emerging field, well-described and validated large animal models that can capture the primary anatomical, physiological, and thrombus characteristics are critical to enable new technical and technological advancements and facilitate the training of new interventionalists. Unfortunately, to the best of our knowledge, no detailed description of a large animal model with interspecies comparisons between swine and humans is available. This study aims to validate and standardize a large animal model for PE with human-derived clots. First, we provide a manufacturing technique for creating human-derived heterogeneous thrombi (radio-opaque and radiolucent) to serve as surrogates for thromboembolism observed in human patients. Second, we provide a detailed comparison of anatomical, physiological, and histological features between the swine and the human pulmonary arteries. Third, we describe step-by-step the technique and tools required to reproduce clinically significant PE consistently.

MATERIAL AND METHODS

Manufacturing technique for human-derived clot analogs and histological analysis

The fabrication method of clot analogs was modified from that previously validated and published.[1,9] Briefly, 72 mL of banked human fresh frozen plasma was mixed with 8 mL red blood cell (RBC) concentrates and coagulation was induced by adding calcium chloride solution. This mixture was then transferred to a polyvinyl chloride tube with ¾ inch (19.05 mm) in internal diameter and 88 cm in length and allowed to coagulate and mature for 24 h. Then, to provide radio-opacity to a subset of a clot analog, emboli were incubated in iodine solution (Omnipaque 350) at 4°C overnight before use. To evaluate the composition of the clot analogs along their length, 1 cm long sections were obtained from each 1/3 of the clot (proximal, middle, and distal following the direction of flow) and fixed for 24 h in 10% buffered formalin. Then, formalin fixed paraffin embedded tissue blocks were created using conventional techniques and cut in 4 μm thickness. Slides were stained with hematoxylin-eosin (H&E) and Martius Scarlet Blue (MSB). Using the Motic Easy Scanner device, the slides were digitized and clot compositional analysis was performed using Orbit Image Analysis Software (www.orbit.bio, Actelion Pharmaceuticals Ltd., Gewerbestrasse, Allschwil, Switzerland.) with a standard operating procedure in our laboratory.

In vivo swine model of PE

Animal procedures were approved by the Institutional Animal Care and Use Committee at our institution. Six domestic pigs with a weight range of 45–65 kg were induced with an intramuscular injection of telazol/xylazine, intubated, and maintained with 2.5–3% isoflurane carried by 100% oxygen. Intra-arterial blood pressure, electrocardiogram, temperature, oxygen saturation, and expired carbon dioxide levels were measured and recorded until the termination of anesthesia. A veterinarian technologist conducted the care of the animal and documentation.

Under ultrasound guidance, the right femoral vein was canalized using modified Seldinger technique and a 26 Fr sheath (Gore Dryseal flex introducer sheath, Flagstaff, Arizona) was advanced over a 0.035 support wire (Amplatz support guide wire, Boston Scientific, Marlborough, Massachusetts) into the inferior vena cava (IVC). To measure the baseline pressures of the animal before embolization, a Swan-Ganz catheter (Edwards Lifesciences, Irvine, California) was advanced through the right femoral vein, the right atrium and ventricle, to the pulmonary arteries under fluoroscopic guidance. At this point, blood pressures in the right ventricle, main pulmonary artery (MPA), and left/right pulmonary artery (LPA/RPA) and the pulmonary capillary wedge pressure (PCWP) were measured. Then, the Swan-Ganz catheter was exchanged for a 6F pigtail catheter which was advanced over a wire into the MPA. Digital subtraction angiography (DSA) along with a rotational 3D image was performed with a biplane Artis Z system (Siemens Healthcare, Forchheim, Germany) to document and measure baseline anatomy of the pulmonary arteries. At this point, human-derived clot analogs (radio-opaque and radiolucent) were introduced through the 26 Fr sheath into the IVC and allowed to spontaneously embolize into the pulmonary artery [Supplementary Material - Video 1]. DSA was conducted to confirm the location and pressures measured to evaluate the severity of the occlusion as described above. Pulmonary angiographies were repeated every 5 min 6 times to document clot integrity and stability of occlusion.

At the conclusion of the test, the animals were euthanized, and a necropsy with grossing of the pulmonary arteries was performed. Pulmonary arteries were harvested and formalin-fixed and paraffin-embedded. Then, 4 μm thickness slices were stained with H&E and MSB and images were digitized and analyzed.

Statistical analysis

Categorical variables are presented as frequency and bar graphic and continuous variables are presented as means ± standard deviation. Mann–Whitney U test was used to compare values between groups. $P < 0.05$ was considered

statistically significant. All statistical analyses were performed using SPSS V.23.

RESULTS

We conducted experiments in six animals. On average, each animal had six human-derived clots injected for a total of 36 clots. By introducing the clots (6 cm long × 1 cm in diameter) into the IVC through the 26 F sheath [Supplementary Material - Video 1], no significant clot fragmentation was observed. There were no device or procedure-related complications observed during the study. All animals survived the recreation of a PE with the occasional need for pharmacological cardiovascular support. The procedure was completed in all the animals.

Interspecies pulmonary anatomical comparison

An interspecies anatomical comparison was performed with de-identified CTA of the pulmonary artery obtained from institutional database and 3D rotational pulmonary angiography from human cadaveric lungs. The MPA bifurcation in humans has an average 99 ± 10° angle,[10] and that is comparable ($P > 0.08$) to the 95° (± 8°) from the angle found in swine PA morphology [Figure 1a and b]. We divided the pulmonary artery branches and found nine main branches in the RPA (R1-R9) and nine main branches in the LPA (L1-L9) [Figure 1c and d].

DSA was used to compare the diameters of the MPA, RPA, LPA, truncus anterior, and interlobar arteries in available patient data with animals weighing 45, 55, and 65 kg [Table 1].[11-13]

With an animal weight of 65 kg, the MPA, RPA, LPA, and Truncus anterior diameters were 24 ± 1.1 mm, 16.5 ± 0.8 mm, 12.6 ± 1.2 mm, and 12.2 ± 0.3, respectively. These measures were compared to human standards as described by Wang *et al*.[11] Our findings suggest that swine MPA and Truncus anterior measurements were comparable to those of an adult human (MPA $P = 0.12$; Truncus anterior $P = 0.37$) [Figure 2].

Histological analysis

The human-derived clot analog after fabrication measured approximately 11–12 cm in length with significant variation of the main components between end to end. Clot analogs showed: (1) portions mainly composed of fibrin (94–96%); (2) portions with a heterogeneous mixture of components (48.9% RBC/51.1% Fibrin) resembling clots extracted from patients suffering from PE;[14,15] and (3) portions mainly composed of RBC (95–96%) [Figure 4a, c, and d]. We can also see the resultant radiopacity acquired by the clot analog after incubation in an iodine solution [Figure 4b].

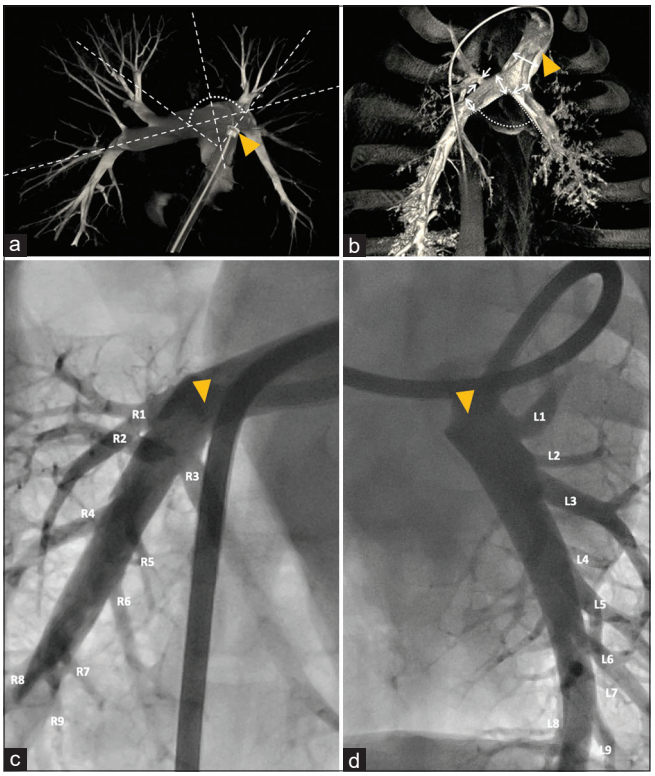

Figure 1: Pulmonary artery (PA) morphology. Antero-posterior fluoroscopic tridimensional reconstructions of the human PA (a) and Swine PA (b) presenting the bifurcation angles and the internal diameters measurement sites (White arrows). Anteroposterior (AP) fluoroscopic view of the swine baseline anatomy in the right (c) and left PA (d). Within the arteries, we can appreciate the tip of the catheter (yellow arrow heads). measurement sites (White arrows). AP view of the swine baseline anatomy in the right (c) and left PA (d). Within the arteries, we can appreciate the tip of the catheter (yellow arrow heads).

Table 1: Interspecies comparison of the pulmonary artery diameters

	Human (mm)[1]	Swine 45 kg (mm)	Swine 55 Kg (mm)	P Value	Swine 65 Kg (mm)	P Value
Main Pulmonary trunk	25.3 (SD 3.4)	18 (SD 0.9)	23.0 (SD 1.2)	P<0.05	24.0 (SD 1.1)	P>0.05
Right Pulmonary Artery	19.9 (SD 2.6)	13.3 (SD 1.2)	16.0 (SD 2.3)	P<0.05	16.5 (SD 0.8)	P>0.05
Left Pulmonary Artery	18.8 (SD 2.5)	18.2 (SD 1.5)	12.6 (SD 2.2)	P<0.05	12.6 (SD 1.2)	P<0.05
Truncus Anterior	12.9 (SD 0.9)	9.5 (SD 0.5)	11.3 (SD 0.5)	P<0.05	12.3 (SD 0.3)	P>0.05
Interlobar Artery	15.2 (SD1.5)	7.7 (SD 0.9)	7.9 (SD 1.1)	P<0.05	12.3 (SD 2.2)	P>0.05

Values are expressed as mean +/- standard error. SD=Standard deviation.

An interspecies histological comparison was done by benchmarking human cadaveric tissue and animal main, right, and left pulmonary artery sections obtained after embolization of the fabricated clots were stained with H&E. Microscopic view of the samples (Magnification ×40) showed a preserved adventitia, a thick media with unharmed elastic lamina and intima. Overall, tissue integrity was preserved. The human and swine pulmonary arteries had comparable wall thickness and similar histologic characteristics except for a slightly thicker tunica media in the swine vessels.[16] Swine arteries walls were not significantly thicker than the human (mean 1.1 ± 0.029 mm vs. mean 0.95 ± 0.026 mm) [Figure 3e and f].

Cardiac and pulmonary pressures

An interspecies physiological comparison was made by benchmarking human standards with data obtained in this study pre- and post-embolization. Pre-embolization mean baseline pressures were MPA 20 mmHg (SD 3 mmHg), RPA 23 mmHg (SD 2.5 mmHg), LPA 24.5 mmHg (SD 2.2 mmHg), and PCWP 12 (SD 3.1 mmHg). The intra-arterial pressure measurements post-occlusion obtained during the experiments are summarized in [Figure 4].[17,18]

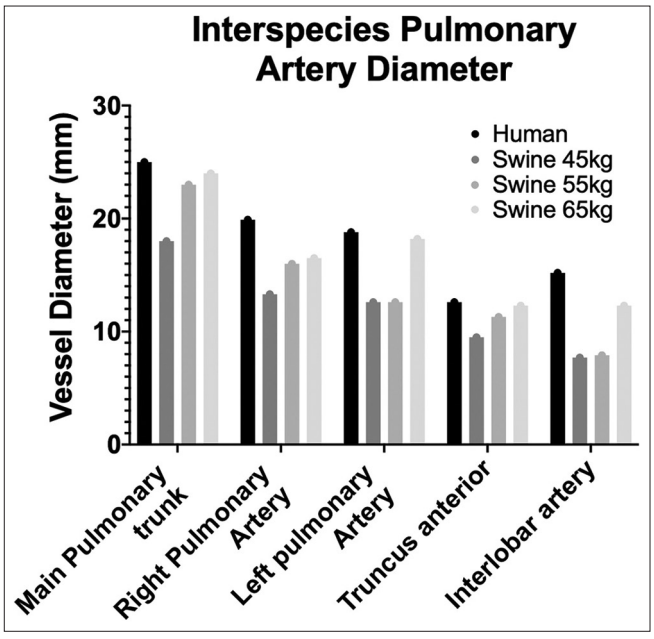

Figure 2: Interspecies pulmonary artery diameter. Bar plots showing the comparison of the human and swine main, right, and left pulmonary arteries, truncus anterior, and interlobar arteries. Six animals were used for this analysis and previously published data from human pulmonary diameters studies. The 65 kg swine main and right pulmonary artery, truncus anterior, and interlobar arteries internal diameters have a non-statistically significant difference compared to the human counterpart $P > 0.05$.

Pulmonary angiography

Radio-opaque human-derived blood clots were followed in real-time using unsubstracted fluoroscopy to confirm the final position in the pulmonary circulation [Supplementary Material - Video 1]. Post-embolization, we evaluated the occlusion at the target artery with contrasted angiography. The occlusion of pulmonary arteries was stable (i.e., no clot fragmentation) in repeated pulmonary angiograms for up to 30 min [Figure 5]. Post-mortem grossing of the pulmonary artery revealed extensive occlusions of the proximal vasculature by cohesive clots adherent to the vascular surface.

DISCUSSION

In our present study, we have presented a swine model of PE and provided comparative data of the pulmonary vascular anatomy and circulatory physiology of swine to that of humans. In addition, we have provided the fabrication process of creating analogous PE clots using banked-human blood and demonstrated the histological makeup. The animal model and clot analogs provide a clinically relevant platform for testing and developing pulmonary thrombectomy tools and techniques.

The current standard of treatment for massive and some cases of high-risk submassive PE are the use of parenteral thrombolysis, catheter-directed therapies, and surgical embolectomy.[2,4,7,8,19] Although effective in decreasing the mortality rate associated with PE, systemic thrombolytic substances add to the risk of major hemorrhagic complications. Considering the inherent complications associated with an open thoracic surgery such as bleeding and infections, surgical embolectomy continues to be a life-saving procedure to treat high-risk PE in patients with absolute contraindications to receive thrombolysis.[2,20-23]

Translational research groups require realistic *in vivo* animal models that mirror human vascular anatomy, physiology, and thrombi characteristics to evaluate the usage of new age technologies and equipment required for percutaneous thrombectomy in PE. Historically, these models have been used to assess the feasibility, safety, and efficacy of new technologies and endovascular equipment. We intended to create a reproducible animal model for endovascular treatments using human blood clot analogs with analogous histologic composition to those observed in pulmonary arteries of PE patients.[15] The previous models simulated an intermediate-high-risk PE, allowing researchers to explore the hemodynamic repercussions of this vascular occlusion. Schultz *et al.* described a contrast-enhanced PE in MRI, investigated biochemical indicators of heart strain in the model, and demonstrated that pigs accurately imitate human hemodynamics during PE, which we corroborated in our investigation. This work used autologous blood to create

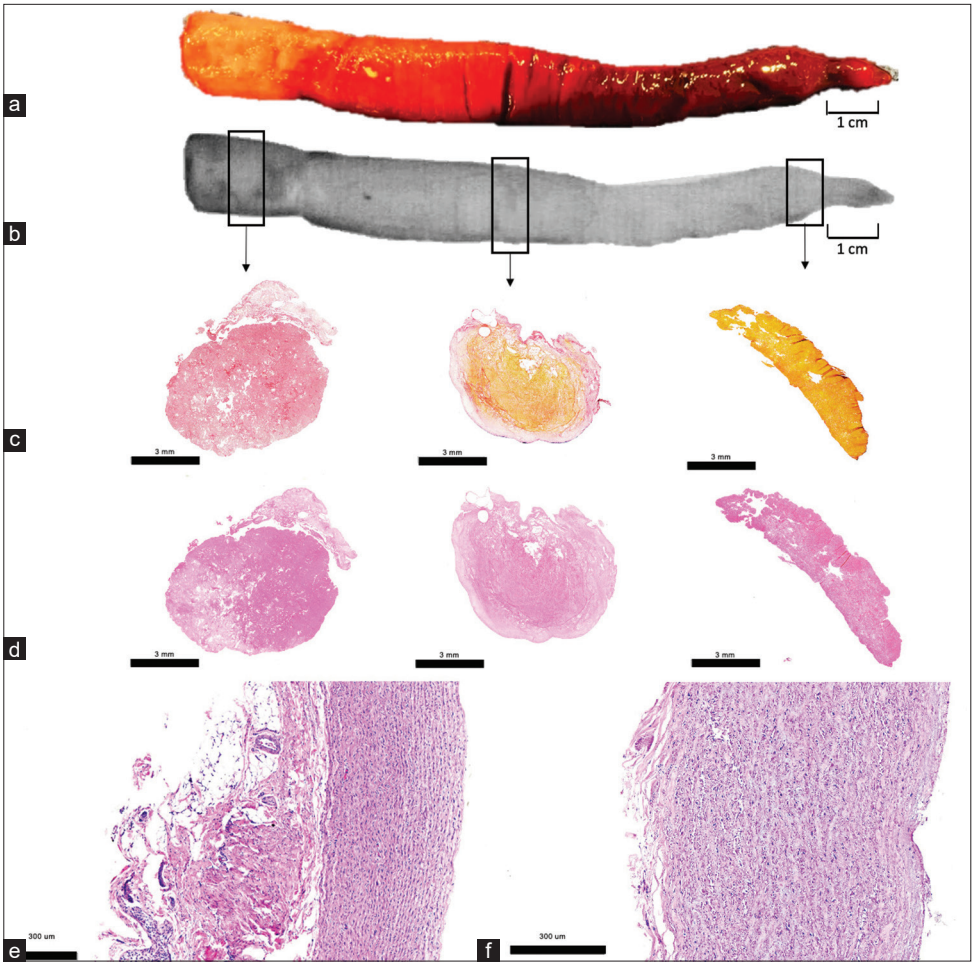

Figure 3: Standardized pulmonary embolism clot analog; Histologic benchmarking of the swine pulmonary artery (PA) versus Human PA. Photograph of a human blood-based clot analog (a) cultivated in Omnipaque 350 for 24 h radio-opacity test of the clot analog showing the points where the histology samples were harvested (b). Martius Scarlet Blue staining (c) and hematoxylin-eosin (H&E) staining (d) of the three main portions of the clot. Scale bars 3 mm. Swine pulmonary artery (e) and human pulmonary artery (f) stained with H&E. Scale bars 300 um.

thrombi without analyzing their structure and components, which are crucial for endovascular therapy of arterial/venous occlusions. Furthermore, whereas MRI accurately depicts the final location of the thrombi, the authors did not perform angiographies (gold standard) or endovascular recanalization with post-procedural histological evaluation of the target arteries.[24] Barbash *et al*. presented a pig model in which they generated an autologous chronic thrombus to be released into the pulmonary circulation. This model could not regulate the final location or size of the thrombus, nor could it perform endovascular recanalization of the PE.[25-28]

To the best of our knowledge, this is the first study aimed at developing a model for pulmonary endovascular procedures, generating radiopaque human-derived clot analogs with histological analysis and thrombus composition validation, and capable of providing an analysis of the animal anatomy with a comparison to the human counterpart. The previous PE clot analogs used aged porcine blood, but their rheological properties could not realistically mimic human PE thrombi. The model was missing an essential feature during the experiments in that case. We tested a wide range of clots resulting in acute PE since the heterogeneous clots we created using human blood products closely matched the histological composition of clots retrieved clinically.

We have provided an in-depth analysis of the vascular geometry of the pulmonary vasculature of swines and their comparability to those of humans. We found that swines with a weight of 65 kg have vessel diameters comparable to human pulmonary arteries, and overall, the arterial geometry is a decent approximation to patients. However, the bifurcation of the swine's pulmonary trunk is significantly steeper and the pulmonary arteries more elongated than the typical

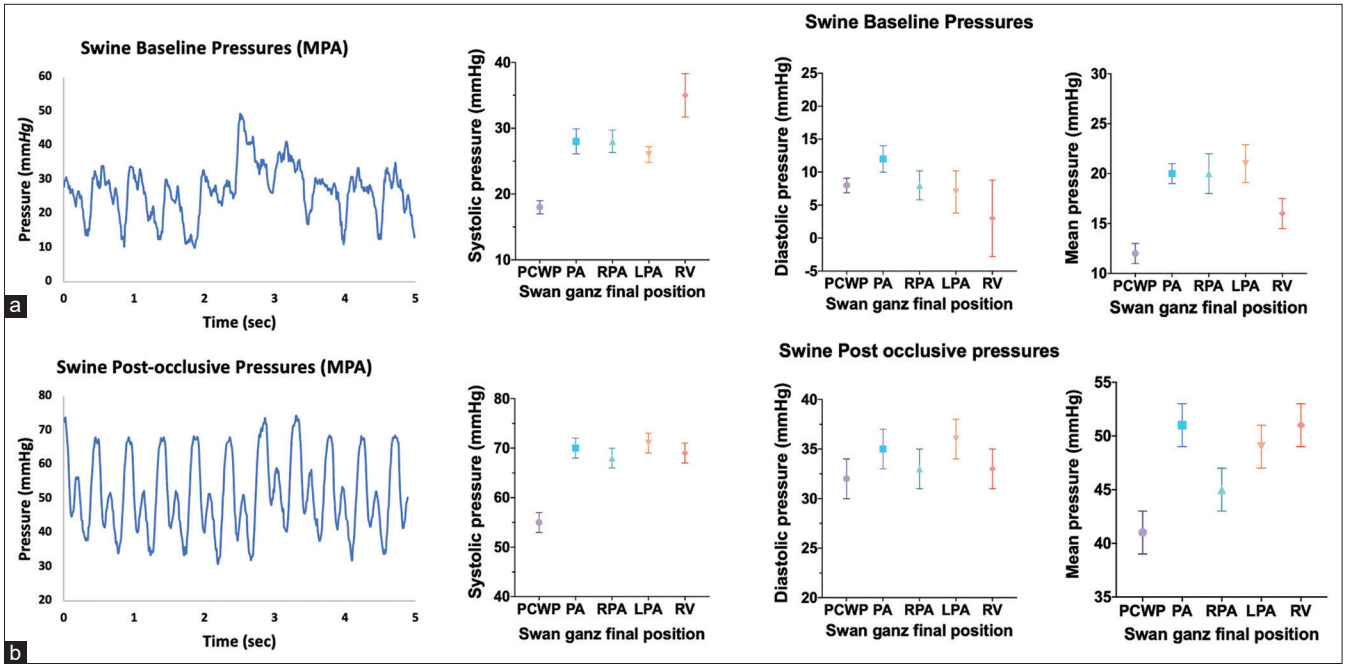

Figure 4: Intra-arterial hemodynamic assessment pre- and post-embolization. *In vivo* chart recordings of several cardiac cycles (5 s) of the baseline pulmonary artery pressures (a) and the changes detected after the embolization of a clot analog (b). Consecutive systolic, diastolic, and mean pulmonary arterial pressure (MPAP) measurements ($n = 40$) were recorded in the main pulmonary trunk, right and left pulmonary artery, right ventricle, and distal pulmonary arteries. The baseline and incremental pressure gradients were analyzed. Values are expressed as mean ± standard error. SD: Standard deviation.

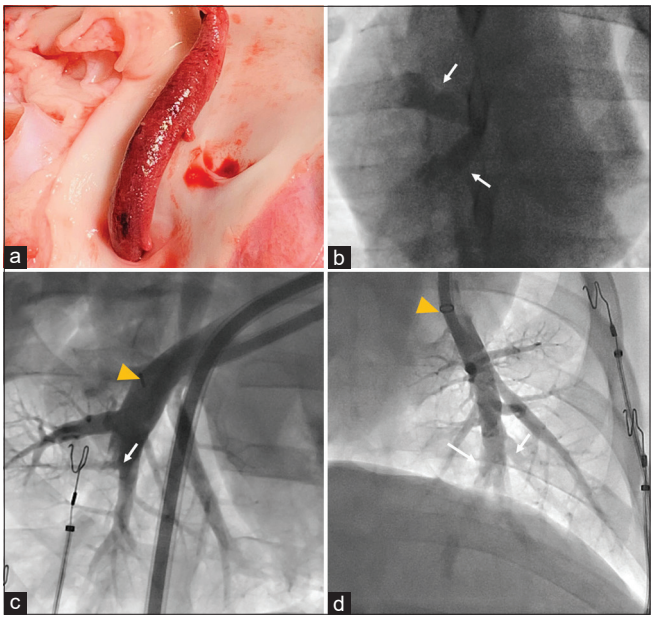

Figure 5: Clot analog embolization. Photograph of a residual clot analog lodged in a distal branch of the right interlobar artery (a). Fluoroscopic image of a radiopaque clot analog lodged in the right pulmonary artery (RPA) and the truncus anterior (b). Anteroposterior fluoroscopic views of the RPA (c) and left pulmonary artery (d) show a distal pulmonary embolism (White arrows) and the tip of the catheter (Yellow arrow heads) within the pulmonary vasculature.

human.[26] The physiological parameters revealed in our studies paralleled those described in the literature for patients with large clot burden (e.g., sub-massive PE), suggesting that this is a representative model from a physiological standpoint.

Few published articles describe the use of autologous swine blood for clot formation.[24,27] In our study, we were able to consistently create clots analogs using banked human blood products. Based on the histological characterization and the *in vivo* behavior, these clot analogs are representative from patients suffering acute PE.[15,9] Because the foundation of our clots was universal donor plasma, the embolization of human-based thrombus inside the pulmonary circulation elicited no rapid immune reaction, lowering the chance of presenting transfusion-related complications in the animal. Although transfusion responses are conceivable during the surgery most likely due to reactions with the RBC components, none of these problems were documented in our series.[29] The creation "on the bench" of clot analogs has many advantages, including: (1) the capacity to manufacture clots of different sizes and lengths by changing the container (or tube) where the blood products is curated; (2) the capacity to generate clots with different amounts of RBC, fibrin and even platelets by mixing different amounts of blood products; (3) the capacity to add radio-opacity to clot analogs to enable fluoroscopic visualization of the clot location, the clot-device

interaction when thrombectomy technologies are used and clot fragmentation/dissolution (spontaneous, mechanical or pharmacological); and (4) the capacity to inject one or more clots as many times as needed in any given animal.

Limitations of our study include the small number of animals used and the lack of *ex vivo* mechanical testing of clot analogs. In this study, we did not perform an analysis of the suitability to test thrombolytic therapies. However, these limitations do not overshadow the overall advantages our model provides for testing of thrombectomy devices for PE.

CONCLUSION

This *in vivo* PE model using clot analogs fabricated from human blood appropriately represents hemodynamic and anatomical characteristics seen in patients and provides a valuable platform to test endovascular tools and techniques to treat PE.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

Financial support and sponsorship

This research received moderate grants for the production of the model; Mayo clinic non-specific grant number for the project.

Conflicts of interest

Luis Savastano and Venu Vadlamudi own stocks in Endovascular Engineering Inc.

REFERENCES

1. Rathbun S. The surgeon general's call to action to prevent deep vein thrombosis and pulmonary embolism. Circulation 2009;119:480-2.
2. LeVarge BL, Wright CD, Rodriguez-Lopez JM. Surgical management of acute and chronic pulmonary embolism. Clin Chest Med 2018;39:659-67.
3. Kuo WT, Banerjee A, Kim PS, DeMarco FJ, Levy JR, Facchini FR, *et al*. Pulmonary embolism response to fragmentation, embolectomy, and catheter thrombolysis (PERFECT). Chest 2015;148:667-73.
4. Deas DS, Keeling B. Surgical pulmonary embolectomy. Crit Care Clin 2020;36:497-504.
5. Hepburn-Brown M, Darvall J, Hammerschlag G. Acute pulmonary embolism: A concise review of diagnosis and management. Intern Med J 2019;49:15-27.
6. Piazza G, Hohlfelder B, Jaff MR, Ouriel K, Engelhardt TC, Sterling KM, *et al*. A prospective, single-arm, multicenter trial of ultrasound-facilitated, catheter-directed, Low-dose fibrinolysis for acute massive and sub-massive pulmonary embolism: The SEATTLE II study. JACC Cardiovasc Interv 2015;8:1382-92.
7. Giri J, Sista AK, Weinberg I, Kearon C, Kumbhani DJ, Desai ND, *et al*. Interventional therapies for acute pulmonary embolism: Current status and principles for the development of novel evidence. Circulation 2019;140:e774-801.
8. Chiarello MA, Sista AK. Catheter-directed thrombolysis for sub-massive pulmonary embolism. Semin Intervent Radiol 2018;35:122-8.
9. Fitzgerald S, Liu Y, Dai D, Mereuta OM, Larco JL, Douglas A, *et al*. Novel human acute ischemic stroke blood clot analogues for *in-vitro* thrombectomy testing. AJNR Am J Neuroradiol 2021;42:1250-7.
10. Knobel Z, Kellenberger CJ, Kaiser T, Albisetti M, Bergsträsser E, Buechel ER. Geometry and dimensions of the pulmonary artery bifurcation in children and adolescents: Assessment *in vivo* by contrast-enhanced MR-angiography. Int J Cardiovasc Imaging 2011;27:385-96.
11. Wang H, Liu K, Wang Z, Zhu Y, Zhao Y, Kong H, *et al*. Computed tomography measurement of pulmonary artery for diagnosis of COPD and its comorbidity pulmonary hypertension. Int J Chron Obstruct Dis 2015;10:2525-33.
12. Pewowaruk R, Mendrisova K, Larrain C, Francois CJ, Roldán-Alzate A, Lamers L. Comparison of pulmonary artery dimensions in swine obtained from catheter angiography, multi-slice computed tomography, 3D-rotational angiography and phase-contrast magnetic resonance angiography. Int J Cardiovasc Imaging 2021;37:743-53.
13. Burman ED, Keegan J, Kilner PJ. Pulmonary artery diameters, cross sectional areas and area changes measured by cine cardiovascular magnetic resonance in healthy volunteers. J Cardiovasc Magn Reson 2016;18:12.
14. Silver MJ, Kawakami R, Jolly MA, Huff CM, Phillips JA, Sakamoto A, *et al*. Histopathologic analysis of extracted thrombi from deep venous thrombosis and pulmonary embolism: Mechanisms and timing. Catheter Cardiovasc Interv 2021;97:1422-9.
15. Chernysh IN, Nagaswami C, Kosolapova S, Peshkova AD, Cuker A, Cines DB, *et al*. The distinctive structure and composition of arterial and venous thrombi and pulmonary emboli. Sci Rep 2020;10:5112.
16. Li N, Zhang S, Hou J, Jang IK, Yu B. Assessment of pulmonary artery morphology by optical coherence tomography. Heart Lung Circ 2012;21:778-81.
17. Reynolds DW, Bartelt N, Taepke R, Bennett TD. Measurement of pulmonary artery diastolic pressure from the right ventricle. J Am Coll Cardiol 1995;25:1176-82.
18. Kovacs G, Berghold A, Scheidl S, Olschewski H. Pulmonary arterial pressure during rest and exercise in healthy subjects: A systematic review. Eur Respir J 2009;34:888-94.
19. Licha CR, McCurdy CM, Maldonado SM, Lee LS. Current management of acute pulmonary embolism. Ann Thorac Cardiovasc Surg 2020;26:65-71.
20. Stein PD, Alnas M, Beemath A, Patel NR. Outcome of pulmonary embolectomy. Am J Cardiol 2007;99:421-3.
21. Takahashi H, Okada K, Matsumori M, Kano H, Kitagawa A, Okita Y. Aggressive surgical treatment of acute pulmonary embolism with circulatory collapse. Ann Thorac Surg

2012;94:785-91.
22. Wadhera RK, Piazza G. Treatment options in massive and sub-massive pulmonary embolism. Cardiol Rev 2016;24:19-25.
23. Ciampi-Dopazo JJ, Romeu-Prieto JM, Sánchez-Casado M, Romerosa B, Canabal A, Rodríguez-Blanco ML, *et al*. Aspiration thrombectomy for treatment of acute massive and sub-massive pulmonary embolism: Initial single-center prospective experience. J Vasc Interv Radiol 2018;29:101-6.
24. Schultz J, Andersen A, Gade IL, Ringgaard S, Kjaergaard B, Nielsen-Kudsk JE. A porcine *in-vivo* model of acute pulmonary embolism. Pulm Circ 2018;8:2045893217738217.
25. Barbash IM, Schenke WH, Halabi M, Ratnayaka K, Faranesh AZ, Kocaturk O, *et al*. Experimental model of large pulmonary embolism employing controlled release of subacute caval thrombus in swine. J Vasc Interv Radiol 2011;22:1471-7.
26. Edwards PD, Bull RK, Coulden R. CT measurement of main pulmonary artery diameter. Br J Radiol 1998;71:1018-20.
27. Kobayashi E, Hishikawa S, Teratani T, Lefor AT. The pig as a model for translational research: Overview of porcine animal models at Jichi Medical University. Transplant Res 2012;1:8.
28. Barbash IM, Schenke WH, Halabi M, Ratnayaka K, Faranesh AZ, Kocaturk O, *et al*. Experimental model of large pulmonary embolism employing controlled release of subacute caval thrombus in swine. J Vasc Interv Radiol 2011;22:1471-7.
29. Smith DM, Newhouse M, Naziruddin B, Kresie L. Blood groups and transfusions in pigs. Xenotransplantation 2006;13:186-94.

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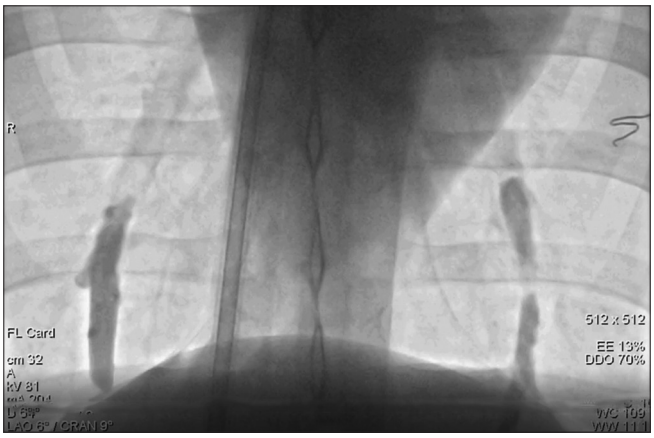
SUPPLEMENTARY MATERIAL



Video 1: Human derived clot analogs embolization